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World Automation Congress

Ninth International Symposium on Robotics with Applications

Orlando, Florida, USA
June 9-13, 2002

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ABSTRACT

This paper describes recent extended field trials performed using the FIDO (Field Integrated Design & Operations) rover, an advanced NASA technology development platform and research prototype for the next planned rover mission to Mars. Realistic physical simulation of the NASA 2003 Mars Exploration Rovers mission was achieved through collaborative efforts of roboticists, planetary scientists, and mission operations personnel. An overview of the objectives, approach, and results is reported.

KEYWORDS: Mars exploration, planetary rover, FIDO, space mission simulation, field trials, autonomous mobile robot, space robotics

1. INTRODUCTION

As an integral part of initiatives to explore Mars, NASA employs mobile robots that are designed to rove across the surface in search of clues and evidence about the geologic, climatic, and aqueous history of the planet. The first autonomous planetary rover, named Sojourner, was deployed on Mars in the summer of 1997 as part of the payload on the NASA Mars Pathfinder lander. Sojourner demonstrated the viability of exploring planetary surfaces using mobile robot technology; its mission, however, was limited to exploration in the proximity of the lander. In 2003, NASA plans to launch a follow-up Mars mission that will use two rovers to explore distinct regions of the planet's surface. These rovers will have greater mobility and autonomy than Sojourner since they are expected to traverse up to 100 meters each Martian day (*sol*) and to explore without relying on surface landers. Objectives for this Mars Exploration Rovers (MER) mission are to be accomplished using the two rovers and their onboard science instruments.

During the spring of 2001, JPL conducted an extended field trial in the California Mojave Desert to physically simulate the mission operations approach planned for one rover of the MER mission. Since the MER rovers were in the design phase at that time, mission personnel made use of JPL's FIDO rover, a MER prototype, and its associated end-to-end field testing infrastructure [1]. The FIDO end-to-end system includes networked operations/command workstations at JPL, satellite communications equipment, remote field networking and support equipment, and an autonomous rover fully integrated with science instrumentation. Twenty sols of MER-like operational sequences were simulated in a complex geological setting analogous to the Martian surface. Mission operators conducted the field trial via satellite at JPL, 180 miles from the test site, without prior knowledge of the site location.

Realistic field trials are a preferred means to verify and validate maturing technologies for autonomous robotics tasks [1-7]. This paper describes activities in this regard with focus on the objectives, approach, and results of the MER-FIDO field trial conducted in 2001. In Section 2, we briefly describe key components of the FIDO system architecture and salient differences between the FIDO rover and the rovers designed for the MER mission. High-level implementation details of the field trial are presented in Section 3, followed by the associated results in Section 4 and concluding remarks.

2. FIDO ROVER AS A MER PROTOTYPE

The FIDO rover represents a central integration platform for the development, rapid prototyping, and testing of advanced robotic technologies. It is a fully functional prototype for the rovers designed to accomplish the objectives of the MER mission (see Fig. 1), and has proven useful to the Mars science community for end-to-end mission concept testing and validation associated with semi-autonomous *in-situ* science exploration via annual terrestrial field trials. The FIDO rover is but one of several autonomous rovers developed at JPL using the FIDO *concept* [1, 8], a functional architecture and infrastructure for the development of robotic mobility platforms. Rovers similar in appearance developed by NASA include the *Athena SDM*, *K9*, and *Rocky 8* rovers. The JPL Athena SDM [9] currently serves as a dedicated navigation/mobility Software Development Model for MER; it features flight-like avionics, but does not carry a full suite of science instruments. The K9 rover is presently being developed to a level of FIDO maturity by the NASA Ames Research Center to investigate the feasibility of autonomous characterization of remote sites using onboard instruments [10]. The JPL Rocky 8 rover, also in the developmental stage, features a distributed control electronics approach, and will serve as a testbed for an object-oriented software architecture presently in its early stage of implementation. These vehicles use mechanical clones of the FIDO mobility system (6-wheel passive rocker-bogie suspension) and chassis design, but differ primarily in proposed electronics and software architectures. FIDO rover hardware and software architecture is the most mature and field-tested of the current NASA technology rovers, thus enabling its role as a flight rover prototype.

FIDO field trial mission operators use the Web Interface for TeleScience (WITS), a JPL-developed web-based toolset for collaborative, geographically distributed robotic science operations [11]. WITS is used as the primary graphical user interface and command sequence generation/uplink tool for the FIDO rover, in conjunction with the Parallel Telemetry Processor (PTeP) and the Multi-Mission Encrypted Communications System (MECS), also developed at JPL. Mission scientists can command the FIDO rover remotely via command uplink from WITS and receive telemetry data products from the rover and its instrument payload. Telemetry downlink is processed by PTeP and distributed by MECS to remote collaborative WITS users across the Internet. While FIDO uplink and downlink communications are achieved via Earth-orbit satellite, the MER mission will use UHF Mars orbiter relay and Direct-to-Earth (DTE) links. WITS will be used on the MER mission as a science activity planning tool — one of several ground-based software tools developed for actual MER operations.

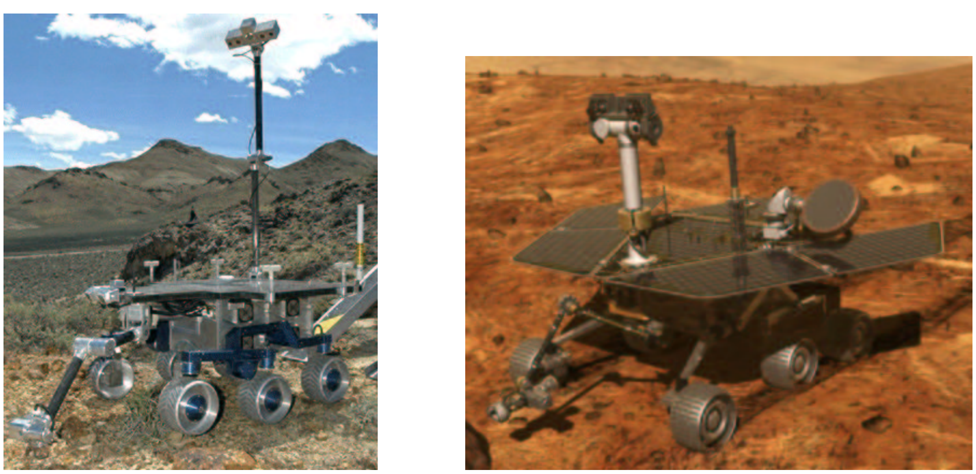

Figure 1. FIDO rover prototype and MER conceptual design.

More detailed technical descriptions and specifications of the critical FIDO subsystems, mission operations tools, and capabilities can be found in [1, 12-16].

2.1 FIDO and MER Rovers: Functional Contrasts and Similarities

Although the FIDO rover is similar in function and capabilities to the MER rovers, the latter are about 1.5 times larger in size and 2.5 times as massive. Solar panels and onboard batteries provide power for each vehicle. From a systems viewpoint, there are subtle functional differences between the rovers' design and configuration in the areas of mobility and sensing for navigation and control. Both designs employ the JPL 6-wheel rocker-bogie suspension and are compatible with respect to motor control and mobility performance, as well as implementations of inertial and celestial [15] navigation sensing. Engineering cameras on each rover include front and rear hazard cameras (Hazcams) used to monitor the terrain in the immediate vicinity while executing onboard hazard detection and avoidance during autonomous navigation.

Less subtle differences exist with regard to robotic mechanism designs in three aspects. Firstly, the FIDO rocker-bogie suspension is designed for all-wheel drive and steer, whereas the MER suspension is designed for all-wheel drive and 4-wheel steer. Secondly, the FIDO instrument arm has four degrees-of-freedom (DOF) (and a passive 5th DOF), whereas the MER rover designs employ a five DOF instrument arm. Finally, the rovers each utilize a different type of mast to carry navigation cameras and remote science instruments. FIDO has a 4-DOF mast arm that is deployable to variable heights above its solar panel up to 2 meters above ground at full extent; the 2-DOF MER mast has a fixed height of 1.3 meters above ground after a one-time deployment. It is apparent from Fig. 1 that the FIDO mast is located at the rear of the vehicle in contrast to the frontal placement of the MER mast, and that the solar array configurations are very different. This results in different near-field obscuration patterns (due to solar panel shape) for the various mast-mounted instruments. To compensate for some of these differences when simulating MER, the FIDO mast is deployed at the MER mast height during the field tests.

A more distinct contrast between the FIDO and MER rovers is the science payload carried by their respective masts and instrument arms. On its mast, each rover carries a color stereo imaging system (Pancam) for high-resolution terrain surveys, a monochromatic stereo imaging system (Navcam) for planning navigation paths over tens of meters, and an infrared point spectrometer (IPS) for measuring mineral composition of surface materials from a distance (so that rocks/soils can be pre-selected for later close-up investigation). The FIDO and MER stereo imaging systems are functionally comparable. However, the IPS instruments differ in that the FIDO IPS detects infrared (IR) light *reflected* from objects while the MER IPS detects thermal IR radiation *emitted* from objects. The FIDO IPS serves as an analogue to its MER counterpart, more accurately referred to as the Miniature Thermal Emission Spectrometer (Mini-TES).

Both rover configurations include a robotic arm beneath the frontal area of the solar panel that carries a suite of instruments used for in-situ science investigation of surface materials. Each instrument is deployed by positioning the arm to achieve accurate placement onto, or in close proximity to, rocks/soil as required. Each instrument arm includes a microscopic imager to capture extreme close-up images and a Mössbauer spectrometer to detect composition and abundance of iron-bearing minerals. FIDO carries a color microscopic imager (CMI) and the MER rovers carry a monochromatic microscopic imager. The Mössbauer spectrometer operates using a radiation source; however, to mitigate costs associated with radiation safety procedures, FIDO operations involving this instrument were executed using a physical model of the spectrometer. A fully functional Mössbauer spectrometer has been used on FIDO in prior field tests [2, 12]. The MER rovers have two additional instruments that are not physically emulated on the FIDO instrument arm. These include an Alpha-Particle-X-Ray Spectrometer (APXS) to determine elemental chemistry of surface materials, and a Rock Abrasion Tool (RAT) for exposing fresh material beneath dusty/weathered layers of rock surfaces. The FIDO Mössbauer mass model and CMI were used to emulate autonomous *placement* of the APXS and RAT, respectively, during the MER mission simulation. For subsequent field tests, physical models representative of these devices could be integrated onto the FIDO instrument arm as well.

3. MARS EXPLORATION ROVERS MISSION SIMULATION

The 2001 MER-FIDO field trial, and its preliminary rehearsal activities, brought together over 40 planetary scientists, spacecraft engineers and operations personnel, and robotics technologists for active participation in a realistic simulation of rover operations planned for the 2003 NASA MER mission. This team constitutes the Science Operations Working Group (SOWG) responsible for conducting the test (and ultimately the mission) from JPL. Two preliminary 2-day rehearsals were held months prior to the field trial at the JPL MarsYard, an outdoor test facility with Mars-like terrain. Each of these tests enabled full-scale and end-to-end FIDO system checkout, as well as initial training of the SOWG. For the extended field trial, the FIDO system was used to physically simulate a 20-sol mission baseline scenario of *MER-A* (one of the two mission rovers) over a 10-day period. The venue for the field trial was a small arroyo on the southern edge of the Soda Mountains in California's Mojave Desert, where a team of 15 field geologists and rover engineers handled all test site activities. Goals and objectives based on high-level MER mission requirements were set to examine how closely they could be achieved using a state-of-the-art rover prototype and best practices derived from recent rover field trial experiences [2, 4, 12].

3.1 Field Trial Objectives and Constraints

The primary objective was for the SOWG to acquire and use FIDO rover instrument and image data to formulate and test hypotheses about the geologic evolution of the field site. Mission operations for the field trial were "blind" and fully remote. That is, the SOWG commanded the rover via satellite communications from JPL, and their prior knowledge of the desert test site was limited to large (tens of square kilometers) aerial thematic imagery and spectral data typical of real Mars orbital observations. The SOWG initially uses the aerial data to generate geological hypotheses about the field site. The SOWG then correlates hypotheses generated from acquired rover instrument data to better understand the field site geology. This use of FIDO is an effective means to train personnel on efficient uses of rovers for conducting traverse science and making *in-situ* measurements in realistic terrains using mission-like data rates, communications, and time pressures. To achieve such objectives, the field trial was conducted under realistic mission constraints on uplink/downlink data volumes, separate UHF and DTE links, timing of communications opportunities between the rover and "Earth", distinctions between critical and non-critical telemetry, and strict daily mission operations timelines. A compressed version of the actual mission timeline was followed in order to complete the 20 sols of operations in 10 test days of 9-hour shifts each. For added realism, various types of impromptu anomalies were staged and introduced during mission operations to exercise SOWG reactions to unexpected events (such as temporary loss of UHF communications assets, loss of transmitted telemetry, degraded rover operations due to extreme temperatures, etc).

3.2 Test Configuration and Approach

The FIDO field test operations facility at JPL is equipped with networked computer workstations running WITS, PTeP, and MECS as well as miscellaneous laboratory and office support infrastructure. Satellite link capability is available via satellite modem connection between networked computers and a 2.4-meter satellite dish antenna allowing remote commanding of the rover via the Internet. To supplement desktop monitors, operator interface screens are projected onto several large screens in the operations area. Any remote members of the SOWG who are situated outside of JPL and the field site use WITS to participate via the Internet. At the desert test site, stand-alone remote equipment infrastructure provides field operations support for the field team and rover. FIDO field support equipment consists of a field trailer containing power supplies, a computer workstation, a laptop command/control computer, an Ethernet hub, a satellite modem, and miscellaneous electronics and mechanical test equipment and tools. The field trailer computers are networked and the satellite modem provides connectivity between the trailer network and a 2.4-meter satellite dish antenna set up in the field outside the trailer. Wireless communication between the FIDO rover and the field trailer is accomplished using wireless Ethernet units — one in the trailer and another onboard the rover. The field trailer also includes a differential GPS unit that communicates with the FIDO onboard GPS unit for determination of rover position relative to a base station antenna mounted to the field trailer (for ground truth measurements only). All FIDO rover uplink commands issued from JPL are routed through the laptop command/control computer before transmission to FIDO via the wireless Ethernet. All telemetry from FIDO is stored on the command/control computer and automatically transmitted to the downlink receiver located at JPL.

Typical field trial mission operations activities may be summarized as follows. The SOWG examines available orbital data and makes an initial plan for rover activities that focuses on traversing the field site while making science observations. On the first sol, the rover is commanded to acquire a 360° panorama mosaic using the Pancam and Navcam. To begin the second sol, the SOWG examines the panorama data, selects targets of interest and generates the first command sequence, which typically calls for acquisition of more imaging data and IR spectra, as well as deploying the instrument arm to acquire data. The next sequence might include a traverse to the first detailed science target identified by the science team. The rover would autonomously execute the traverse and acquire detailed images and spectra of the target. Similar traversal and measurement activities are repeated throughout the field trial to yield numerous data products including images, spectra, and engineering telemetry. The FIDO onboard software handles all uplink command sequences, autonomous execution under the VxWorks real-time operating system, and downlink of telemetry.

The approach taken in the field trial to emulate the corresponding data acquisition and effective results of MER Mössbauer spectrometer, APXS, and RAT deployments is as follows. For the Mössbauer and APXS, MER scientists obtained spectral data of representative rocks from the field site prior to the field trial. When FIDO emulated Mössbauer or APXS measurements on a rock in the field, the Mössbauer mass model was placed onto the target and the spectral data for the representative rock type was made available to the SOWG via the downlink processing tools at JPL. When Mini-TES measurements of a specified target were commanded, the FIDO mast would deploy to point the IPS at the target. Actual data acquired from the target by a separate field-capable thermal emission spectrometer (operated by field personnel at the test site) would then be transmitted to JPL and made available via the downlink processing tools. This data was used to supplement data also collected by the FIDO IPS. To emulate the effect of the RAT, field personnel used a hand-held rock grinding tool. When RAT operations were commanded, FIDO would place its CMI near the target while field personnel used the hand-held tool to expose a 5×5 cm^2 area to a depth of ~5 mm (as the MER RAT is designed to do). Subsequently, a close-up CMI image of the abraded surface would be acquired for downlink.

4. MER-FIDO FIELD TRIAL RESULTS

Efforts of the SOWG and FIDO field team culminated in a very successful mission simulation. The FIDO system, with improvements for enhanced mission fidelity [17], enabled the SOWG to exercise specific end-to-end operational sequences proposed for MER-A. Activity sequences executed in the field included autonomous traversal to specified targets, approaching rock targets and deploying multiple instruments, and using a rover wheel to excavate a soil trench, including acquisition and analysis of associated imagery and spectroscopy. Table I summarizes the science data types and downlink volumes returned throughout the 20-sol operation (entries are in megabytes, and include rover state telemetry volume).

Some representative data products are shown in Figs. 2 and 3. Fig. 2 shows the Navcam panorama acquired at the beginning of the field trial, FIDO with mast deployed at the MER height for remote sensing, and sample remote science data products. Fig. 3 shows the FIDO arm deploying multiple instruments, a resulting CMI data product sample, and a front Hazcam image of the deployed arm during data acquisition.

The gross path traversed by the FIDO rover is shown in Fig. 4 as an overlay of black line segments in a close-up view of an aerial image that includes the desert arroyo site. Ground-level images are also shown depicting the rover at the start, middle, and end of the traverse. The terrain in which the rover traversed was representative of a narrow wash that typically was 10 meters across the wash at its most narrow point. The FIDO rover traversed a total distance of 135 meters over the desert terrain throughout the extended field trial. A number of short and long traverses were interspersed among many stationary science investigation activities. The longest continuous autonomous traverse was 40 meters, and the average rover speed during traverses was 60 meters per hour while negotiating and avoiding obstacles and terrain hazards. A full set of data and findings from the field trial are archived on the World Wide Web in the format of an Analyst's Notebook, detailing daily operations and containing both raw and derived data for use by the planetary scientific community (see hyperlinks at http://fido.jpl.nasa.gov).

Table I. Summary of MER-FIDO Field Trial Data Return

Remote science data and imagery				
Instrument Data	**Color Pancam Stereo Images**	**Mono. Navcam Stereo Images**	**IPS Spectra**	**Field Emission Spectra**
Data Items	504	279	177	30
Data Volume (MB)	929.0	171.0	2.6	0.009
In-Situ science data and engineering imagery				
Instrument Data	**CMI Images**	**Mössbauer Spectra**	**APXS Spectra**	**F/R Hazcam Stereo Images**
Data Items	66	5	6	78
Data Volume (MB)	60.8	0.0015	0.0018	47.8

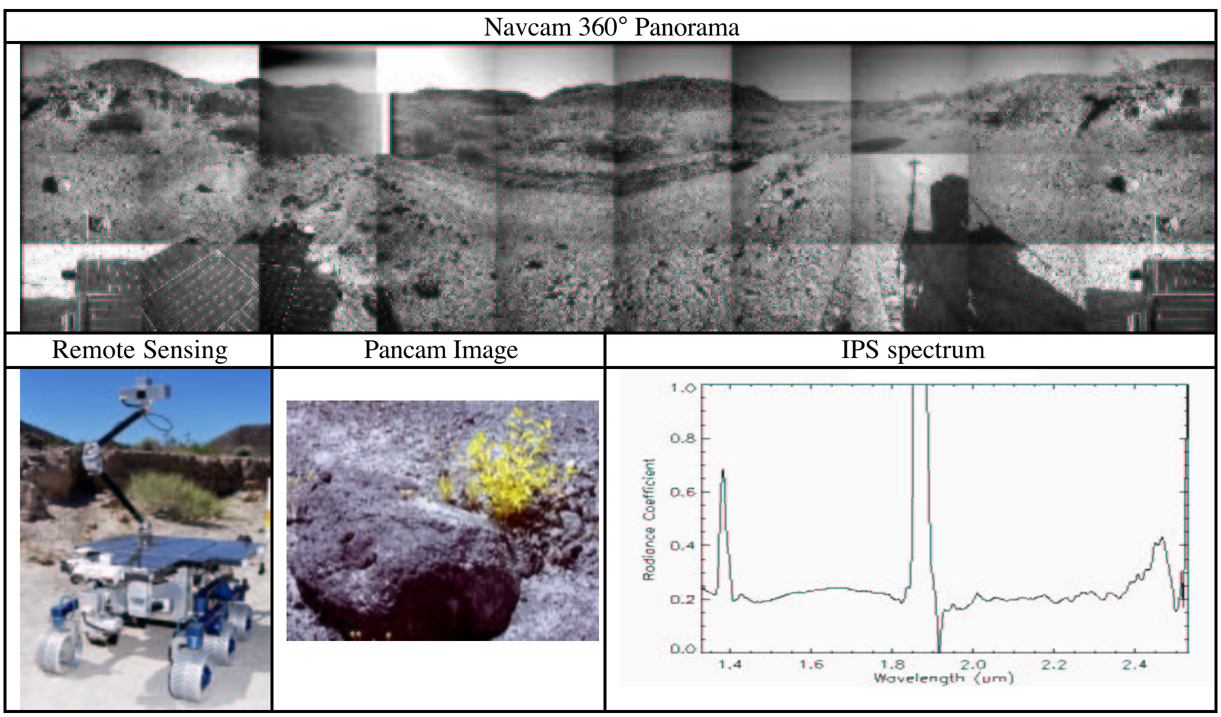

Figure 2. Representative remote science data products.

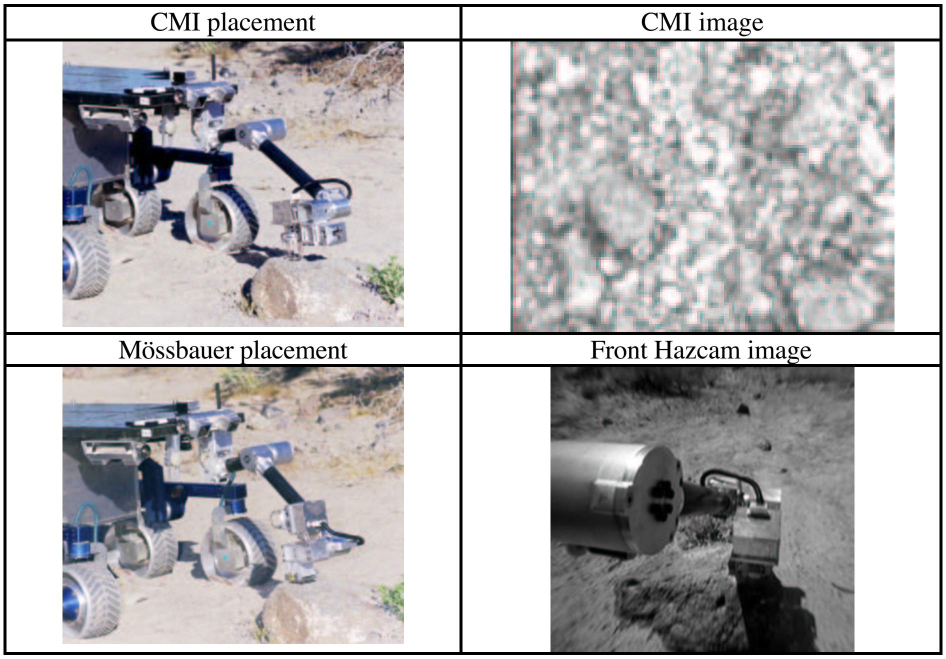

Figure 3. Representative in-situ science data products.

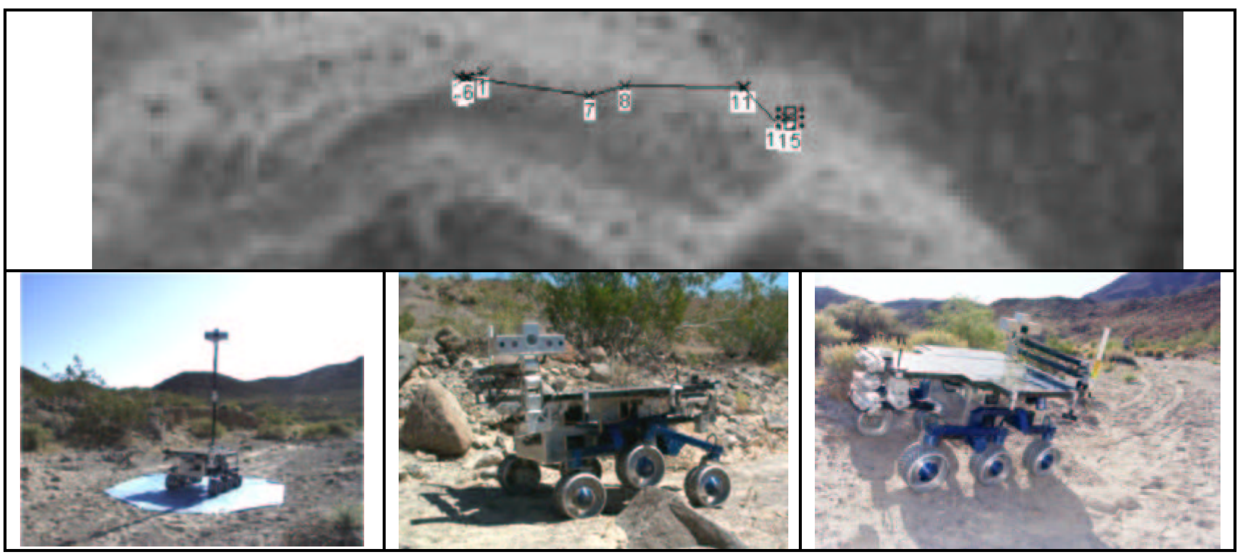

Figure 4. FIDO rover traverse at Mojave Desert site.

5. SUMMARY AND CONCLUSION

Autonomous planetary rovers may be thought of as robotic field geologists that serve as scientific assistants in the exploration of planetary surfaces. This paper provided an overview of the NASA 2003 MER mission simulation experience using the terrestrial prototype, FIDO, to emulate one of the flight rovers. A systems-level description of FIDO as a MER prototype vehicle was given via functional comparisons of the respective rover designs. Details of the 2001 MER-FIDO field trial were covered describing its objectives, approach, and results.

The field trial was a significant event for the NASA Mars Exploration Program, representing a rare and fully immersed collaboration between planetary scientists, spacecraft engineers, and robotics technologists. The participants found the overall experience to be extremely successful. Such field trials are valuable rehearsals as well as proving grounds for proposed rover mission operations. They provide opportunities to test sequences in realistic settings, train mission personnel on how to use autonomous rovers to conduct remote field-based science, and identify technologies that require additional development and/or evaluation. FIDO field experience to date [1, 2] has shown that these terrestrial system analogues reduce mission risk, providing cost-efficient integrated technology development, testing and evaluation within a mission-relevant environment, with direct participation of mission personnel.

Acknowledgments
The research described in this paper was performed at the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. The collaboration and support provided by the NASA Mars Exploration Rovers Project and personnel is gratefully acknowledged, with special regard to John Callas of the MER Science Office at JPL, and the MER Principal Investigators, Steve Squyres of Cornell University and Ray Arvidson of Washington University, St. Louis.

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